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Determining the (n,γ) cross section of ^{153}Gd using surrogate reactions

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Abstract. The astrophysical s -process is responsible for the synthesis of many of the nuclei heavier than iron through a series of low-energy (n,γ) reactions and β -decays. For nuclei for which the neutron capture and β -decay rates are comparable, the branching is crucial for tests of s -process models. Direct measurements of (n,γ) cross sections for these nuclei are extremely challenging due to the inherent difficulties associated with radioactive targets and the low intensity of available neutron beams. The surrogate reaction technique can be used to circumvent these difficulties by creating the same compound nucleus through light-ion reactions on a stable target. The cross section can be determined by combining optical model calculations for the formation of the compound nucleus with the measured exit channel probability for γ -ray emission. We have collected data to determine the low-energy (n,γ) cross section for the unstable nucleus ^{153}Gd by bombarding a stable ^{154}Gd target with protons from the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory to create the desired $^{154}\text{Gd}^*$ compound nucleus. The STARS/LiBerACE silicon and clover germanium detector arrays were used to detect γ -rays in coincidence with the scattered protons. Additional cross section measurements using ^{156}Gd and ^{158}Gd targets will be compared to direct measurements of the (n,γ) cross sections for ^{155}Gd and ^{157}Gd . The current status of the analysis is summarized.

Keywords: Surrogate reactions, s -process, branch point nuclei, compound nucleus

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INTRODUCTION

The astrophysical s -process [1] is believed to be responsible for the synthesis of half the nuclei heavier than iron. These isotopes are created through a series of low-energy (n,γ) reactions and subsequent β -decays of the generated radioactive nuclei. For unstable nuclei that have sufficiently long half-lives (of order weeks and longer), the time scales for neutron capture and β -decay can be comparable. The competition

between these two processes determines the path followed by the s -process. As stellar models provide more quantitative descriptions of nucleosynthesis, more precise nuclear physics input is needed to understand and constrain these models.

However, due to the inherent challenges associated with radioactive targets and the low intensity of neutron beams, direct measurements of the (n,γ) cross sections for these s -process branch nuclei are extremely challenging. To date, heroic direct

calorimetric measurements have reached precisions of ~10% for isotopes with half-lives of ~100 years [2]. This type of measurement becomes even more difficult for isotopes with shorter half-lives. Activation measurements can be performed on shorter-lived samples; however, the requirement that the product nucleus must also be radioactive eliminates most branch-point nuclei (see, for example, Ref. [3] for a recent measurement).

The surrogate reaction technique can be used to indirectly determine cross sections of two-step reactions that proceed through a compound nucleus (see Ref. [4] for details) that are inaccessible to direct measurement. Cross sections can be determined by combining optical model calculations for the formation of the compound nucleus with the measured exit channel probabilities (which are challenging to calculate reliably). Experimental [5] and theoretical [4] efforts at Lawrence Livermore National Laboratory have demonstrated the technique's utility for determining (n,f) cross sections for actinide nuclei. For these experiments, the desired compound nucleus formed in neutron capture on a radioactive nucleus is instead created in a light-ion reaction on a stable target. We are expanding these efforts to determine (n,γ) cross sections for s -process branch point nuclei. In this conference proceeding we discuss the current status of the analysis to determine the low-energy (n,γ) cross section for the unstable nucleus ^{153}Gd ($t_{1/2}=240$ days) using surrogate reactions.

EXPERIMENT

We are analyzing data to determine the low-energy (n,γ) cross section for the unstable nucleus ^{153}Gd with the surrogate reaction technique by inelastically scattering protons on ^{154}Gd to generate the desired $^{154}\text{Gd}^*$ compound nucleus. The experimental set-up is shown schematically in Figure 1. Self-supporting Gd metal targets were bombarded with ~2 nA of 22 MeV protons from the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory for ~50 hours in May, 2007. The scattered protons are detected using the Silicon Telescope for Reaction Studies (STARS) array. The target chamber and STARS array are surrounded by the Livermore-Berkeley Array for Collaborative Experiments (LiBerACE) which consists of five clover HPGe detectors with BGO Compton-suppression shields to detect γ -rays.

The exit channel probability, $P_{(p,p\gamma)}$, for the radiative neutron capture can be measured by comparing the number of $p\text{-}\gamma$ coincidences relative to the total number of protons scattered off of Gd nuclei (after accounting for efficiencies). The excitation

energy of the Gd nucleus, E_{ex} , is determined from the relation

$$E_{ex} = E_{beam} - (E_p + E_{deadlayers} + E_{recoil}) \quad (1)$$

where E_{beam} is the energy of the proton beam striking the target, E_p is the measured proton energy scattered from the target, $E_{deadlayers}$ is the energy lost to target and detector deadlayers, and E_{recoil} is the recoil energy imparted to the Gd nuclei (inferred event-by-event from the scattered protons). The probability is then given by

$$P_{(p,p\gamma)}(E_{ex}) = \frac{(1 + \alpha_{IC})}{\epsilon_\gamma f} \times \frac{N_{(p,p\gamma)}(E_{ex})}{N_{(p,p)}(E_{ex})} \quad (2)$$

where $N_{(p,p\gamma)}$ is the number of observed $p\text{-}\gamma$ coincidences, $N_{(p,p)}$ is the total number of observed protons, f is the fraction of de-excitation cascades that decay via the transition of interest, and ϵ_γ and α_{IC} are the γ -ray detection efficiency and internal conversion coefficient for this transition.

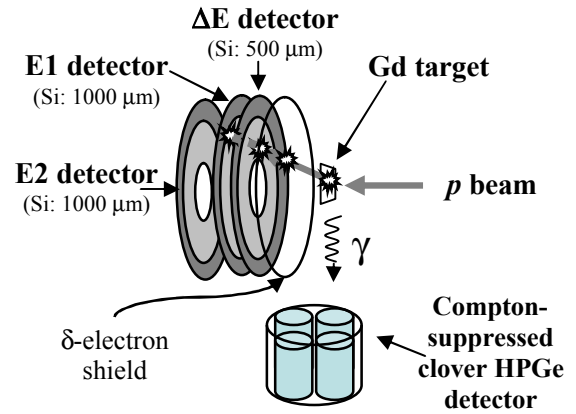


FIGURE 1. Schematic lay-out of experimental set-up. The proton beam from the 88-Inch Cyclotron bombards a Gd metal foil target. The scattered protons are detected in coincidence with γ -rays using the STARS/LiBerACE silicon and clover HPGe detector arrays. Only one of the five clover HPGe detectors is shown. Figure is not drawn to scale.

In addition, as an important benchmarking of the technique, similar surrogate reaction measurements using targets of ^{156}Gd and ^{158}Gd were performed and will be compared to directly measured results for stable ^{155}Gd and ^{157}Gd isotopes [6].

Gadolinium Targets

Four isotopically-enriched, self-supporting, gadolinium metal foils of thickness ~1 mg/cm² were rotated one at a time into the proton beam. A ^{154}Gd

target was used to measure the unknown $^{153}\text{Gd}(n,\gamma)$ cross section and ^{156}Gd and ^{158}Gd targets were used to benchmark the technique by measuring the $^{155}\text{Gd}(n,\gamma)$ and $^{157}\text{Gd}(n,\gamma)$ cross sections. An additional target, ^{155}Gd , was required to determine the $^{155}\text{Gd}(p,pn\gamma)$ background from the 17.5% contamination of ^{153}Gd in the enriched ^{154}Gd target.

Particle Detection

The STARS array consisted of three highly-segmented S2 detectors [7] operated as a ΔE -E1-E2 telescope to identify the protons and determine the energy and vector momentum. Each detector was independently calibrated using a ^{226}Ra α source. Deadlayers in the α source and detector array could be very accurately accounted for by analyzing the α energy dependence on detector impact angle. When cooled to 10^0C , the full-width at half maximum energy resolution was ≈ 150 keV.

γ -ray Detection

The efficiency of the clover detector array, ϵ_γ , was calibrated offline using standard ^{152}Eu , ^{133}Ba , and ^{207}Bi sealed sources immediately after data collection. The detection efficiency inferred online from p - γ - γ coincidences in $6^+ \rightarrow 4^+$ to $4^+ \rightarrow 2^+$ to $2^+ \rightarrow 0^+$ ground-state band cascades agreed well with the offline calibration. The photopeak efficiency for the entire array ranged from 0.5 to 2.5% for the γ -rays of interest. Calculated internal conversion coefficients (α_C) were used for the analysis of these $E2$ transitions.

At excitation energies below the neutron separation energy (S_n), the nucleus de-excites only through γ -ray emission. This spectrum is shown for ^{158}Gd in Figure 2(a). Above S_n , neutron emission is more probable, so excited-states of ^{157}Gd are populated by (p,pn) reactions yielding a spectrum with many γ -ray lines (see Figure 2(b)). Above S_n , the determination of the number of γ -rays from the $(p,p\gamma)$ reaction must take into account these backgrounds from $(p,pn\gamma)$ reactions. As an example, the $2^+ \rightarrow 0^+$ transition (79.5 keV) in ^{158}Gd is the dominant low-energy transition below S_n , but above S_n , the intensity of this transition drops rapidly and a different transition (at 76.9 keV) from ^{157}Gd becomes dominant (see Figure 2(c) and (d)). The centroid and resolution of the lines of interest were determined from fits to the clean, high statistics data below S_n ; these values were used for fits above S_n . Only the amplitudes of the transitions of interest and any nearby transitions from $(p,pn\gamma)$ reactions were allowed to vary in the fits.

EXIT CHANNEL PROBABILITIES

Inserting the results of the analysis into Equation 1 we get the exit channel probabilities of interest. Preliminary results for $P_{(p,p\gamma)}$ for $^{158}\text{Gd}(p,p\gamma)$ are shown in Figure 3. For each of the ground-state band transitions shown, the γ -ray exit channel probability drops rapidly above $S_n=7.937$ MeV; below S_n the probability is nearly constant, which we interpret as the value for f (see Equation 1) because at these energies $^{158}\text{Gd}^*$ only de-excites through γ -ray emission.

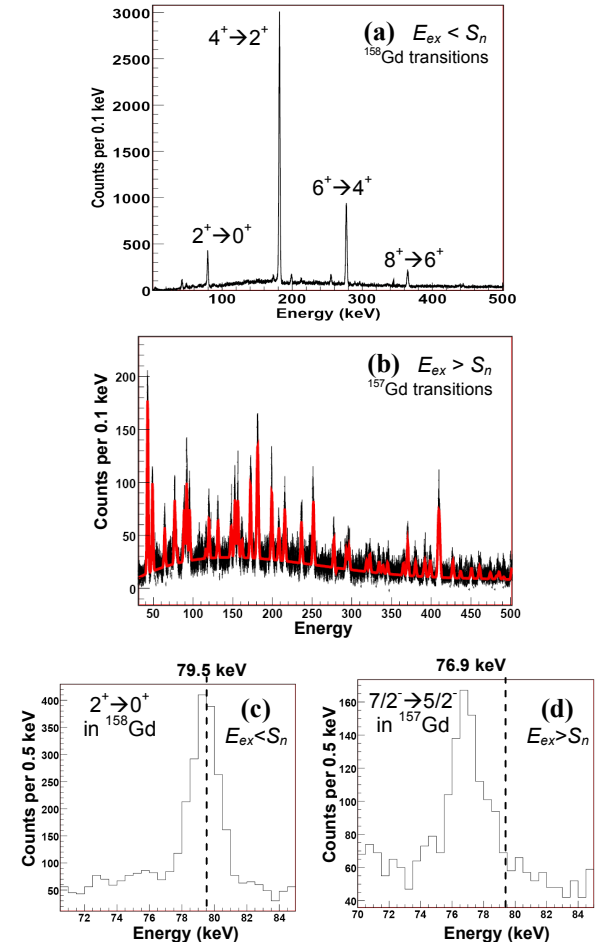


FIGURE 2. Sample γ -ray data for ^{158}Gd . (a) For excitation energies below S_n , the strongest lines correspond to the ground-state band transitions. (b) Above S_n , many transitions in ^{157}Gd can be observed. The data is shown with a smooth line fit through the strongest lines at known transition energies. (c) For excitation energies 1-2 MeV below S_n , the only observable line around 80 keV is from the $2^+ \rightarrow 0^+$ transition in ^{158}Gd . (d) At 1-2 MeV above S_n , a different line dominates: the $7/2^- \rightarrow 5/2^-$ transition in ^{157}Gd .

J^π Sensitivity

At the low-energies of interest to *s*-process astrophysics (typically 0-300 keV), the Weisskopf-Ewing limit is not satisfied and angular-momentum considerations can be important. Theoretical studies performed in Ref. [8] have investigated the sensitivity of (n,γ) reactions to the J^π distribution and concluded that a mismatch between the (n,γ) and the surrogate reaction can have a large impact on the interpretation of a surrogate measurement at low-energy. The J^π distribution in the surrogate measurement can be constrained by analyzing the intensities of discrete γ -ray transitions as mentioned in Ref. [8]. In addition, the benchmark measurements using ¹⁵⁶Gd and ¹⁵⁸Gd targets will aid in understanding and accounting for the impact of any J^π mismatch. A detailed analysis to account for the effects of any J^π population mismatch is currently underway.

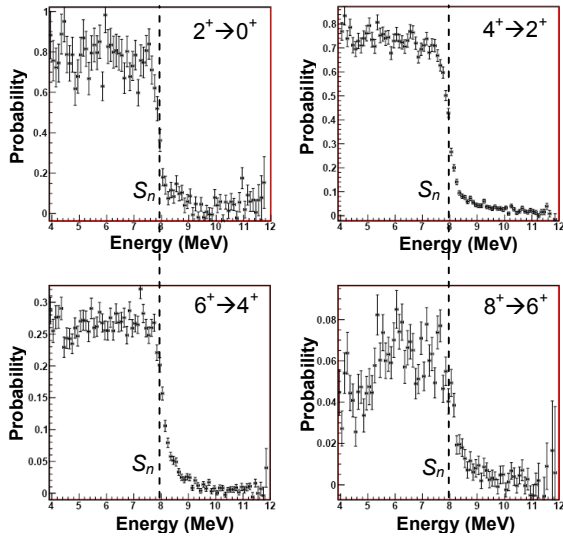


FIGURE 3. Preliminary results for the probability $P_{(p,p\gamma)}$. Results are shown for the lowest four transitions of the ground-state band in ¹⁵⁸Gd. S_n is shown as a vertical dashed line in the plots. Above S_n , the probability rapidly drops to nearly zero as expected. In each case the probability is nearly constant below S_n , and this value gives f (see Equation 1) for the transition.

CONCLUSIONS

We are developing a new technique to measure the (n,γ) cross-section of short-lived isotopes for which direct measurements are experimentally inaccessible. These cross-sections are especially important for *s*-process branch-point nuclei which determine the path

followed by nucleosynthesis. We have collected data to determine the low-energy (n,γ) cross-section for ¹⁵³Gd through the surrogate reaction $(p,p\gamma)$ on stable ¹⁵⁴Gd. The cross-sections for ¹⁵⁵Gd(n,γ) and ¹⁵⁷Gd(n,γ) are also being determined in a similar manner and will be used to benchmark the technique and understand any J^π population mismatch between the desired and surrogate reaction. In addition to ¹⁵³Gd, many other *s*-process branch-point nuclei (such as ⁹⁵Zr, ¹⁴⁷Nd, and others) are accessible to study to using surrogate reactions.

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